Verification of AL800 Garnet Material Properties Using a Test Cavity

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To design an RF cavity that uses transversely biased gyrotropic material for frequency tuning, magnetic properties of the material must be well defined. In the second harmonic Booster cavity [1], Al-800 garnet was chosen as a material for the tuner; static permeability of this material was studied in [2] and the RF loss factor was found in [3]. These studies were made using available at the time magnetic and RF systems that were not optimized for the task; as a result, to extract needed information, iterative approach was used to compare data obtained by magnetic and RF measurements with predictions of modeling. Results of these studies were summarized in [4].

Tunable accelerating cavity is a relatively large scale device. To minimize the probability of a failure due to hidden flaws, static and RF magnetic properties of the material found in [2] and [3] must be verified by direct RF measurements. For this verification, a special "test" cavity has been designed and built that could be tuned in the frequency range required for the second harmonic Booster cavity (75 MHz to 105 MHz). This test cavity was partially filled with ferrite and immersed in the magnetic field of the solenoid [5] previously used for the studies in [2] and [3]. For several settings of the current in the solenoid, frequency and quality factor were measured; this data was compared with results of modeling.

Geometry of the test cavity and the measurement setup are shown in Fig. 1; magnetic system (solenoid) is specified in [2].

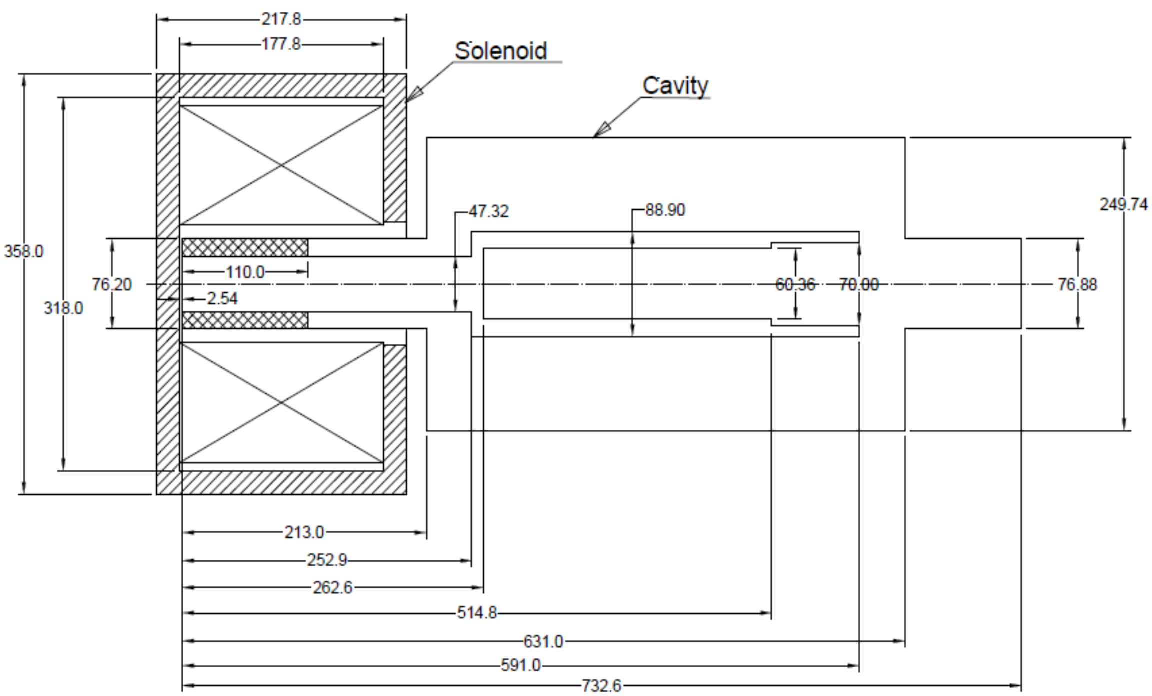

Fig. 1. Geometry of the cavity and setup of the verification test

First iteration of the test cavity modeling was attempted with the use of the material properties summarized in [4]. Fig. 2 and Table 1 specify static magnetic properties of the material that were found in [2]. Fig. 3 shows the behavior of the magnetic loss coefficient **α** found in [3] as a function of the current in the solenoid [5] that was used to generate magnetic field.

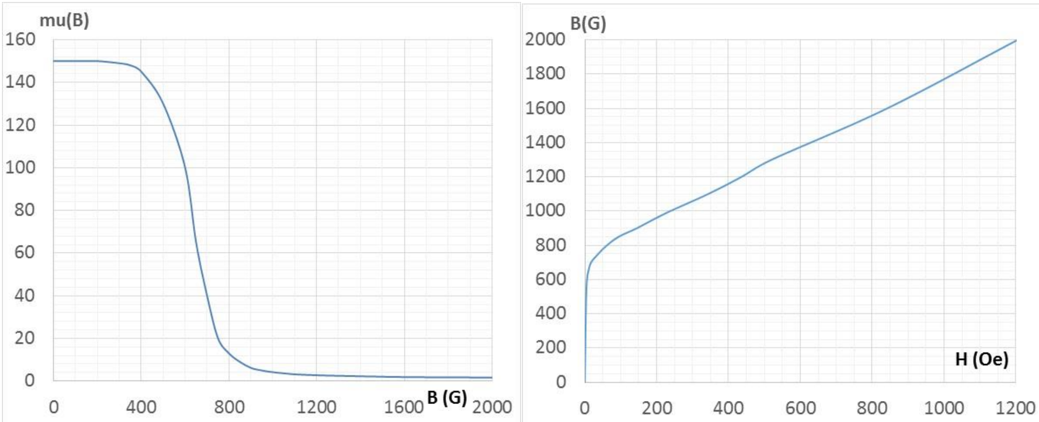

Fig. 2. AL800 Garnet material magnetization curve.

Table 1: Tabulated static magnetization curve of AL800 garnet material.

H (Oe)	0	1.33	2.36	2.76	3.85	6.00	10.00	17.5	37.5	61.54	94.44	145.16	343.75
B (G)	0	200	350	400	500	600	650	700	750	800	850	900	1100
μ	150	150	148	145	130	100	65	40	20	13	9	6.2	3.2

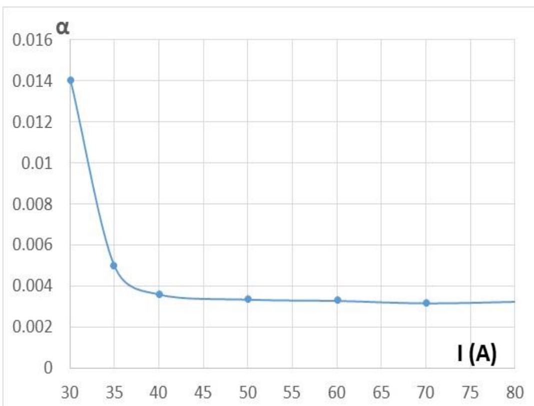

Fig. 3. RF magnetic loss coefficient dependence on the current in the solenoid.

The main finding of [3] was that the loss coefficient **α** is a constant in a wide range of the magnetic fields and frequencies. According to [6], dimensionless **α** can be expressed in terms of the line width parameter ΔH:

$$\alpha = \mu_0\gamma/2\omega\cdot\Delta H = 10^{-7}\gamma/f_0\cdot\Delta H$$

where $\gamma = e/m_e = 1.76\cdot10^{11}$ C/kg is the gyromagnetic ratio and $\omega = 2\pi\cdot f_0$ with $f_0 = 9.4\cdot10^9$ Hz. If magnetic field is expressed in Oe, the loss factor $\alpha \approx 1.5\cdot10^{-4}\cdot\Delta H$.
Using $\alpha = 0.0035$ (as it is in Fig. 3), we get $\Delta H = 23.3$ Oe, which is close to what was specified by the vendor of the material: $\Delta H = 24$ Oe. So, RF magnetic properties of the biased ferrite material, namely the real and the imaginary parts of the complex permeability, were defined using the expressions derived in [4] (equations /4/ and /5/) with the loss coefficient α = 0.0035.

Magnetic field in the blocks of the tuner of the test cavity is strongly non-uniform, especially at low currents. To have acceptable resolution and accuracy of the modeling, mesh in the area of the tuner must be made sufficiently fine. Even finer mesh must be made for the areas with greater expected non-uniformity of the magnetic field. Fig. 4 shows areas of the cavity with fine meshing; area of the cavity in Fig. 1 containing ferrite material is rotated 90º counterclockwise.

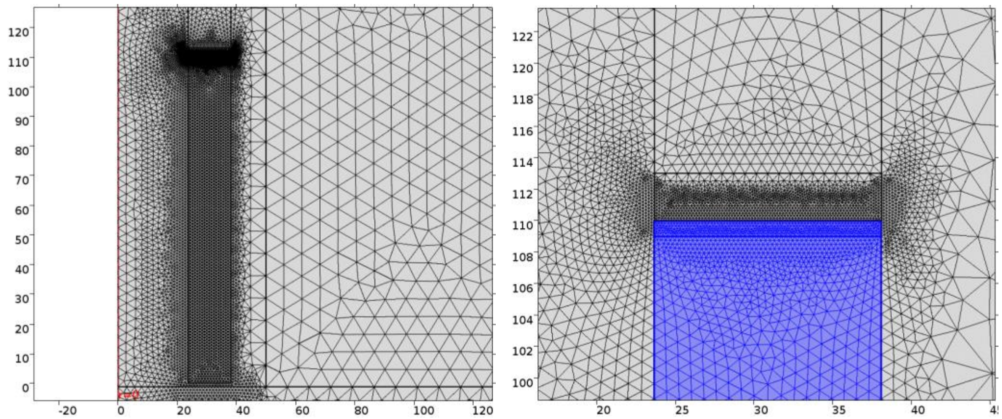

Fig. 4. Meshing the areas of the tuner with expected high non-uniformity of magnetic field.

Figures 5 and 6 compare frequency and the quality factor of the test cavity obtained by the modeling with the results of direct RF measurements.

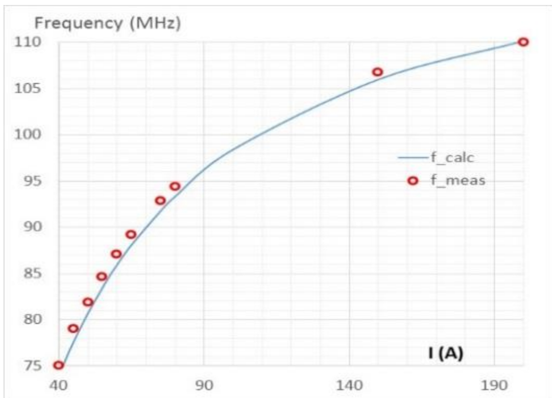

Fig. 5. Frequency of the test cavity as a function of the bias current

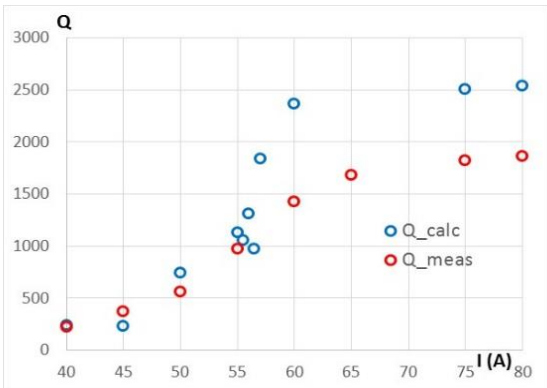

Fig. 6. Calculated and measured quality factor of the test cavity as a function of the bias current

Although calculated frequency dependence on the bias current closely follows the measurement data and the calculated cut-off frequency of the cavity is also close to what was measured, values of the quality factor at high bias current obtained by modeling are significantly higher than the measured. The following reasons of this discrepancy can be imagined: using a wrong model for the garnet material properties or wrong assumption about the quality factor of the cavity without any filling.

Before the impact of these factors is investigated, some explanation must be suggested for the pulsations of the calculated quality factor seen in Fig. 6 (blue circles). The amplitude and the frequency of these pulsations appeared to be a function of the mesh size in the area with high magnetic field non-uniformity. Very fast change of the static permeability with the bias current seen in Fig. 2 combined with a very sharp increase of the RF losses in the vicinity of the gyromagnetic resonance according to [4] require very small mesh size to avoid numerical instability associated with high gradients of these material property values. Mesh shown in Fig. 4 is small enough to keep the frequency and the amplitude of this numerical instability in the acceptable range. Fig. 7 shows a map of the magnetic field in the area near the border of the garnet block at 50 A bias current, which sets the frequency at ~81 MHz according to Fig. 5. In the same figure, a map of the static permeability is shown. We see that the scale of the permeability change rate is as high as ~200 1/mm.

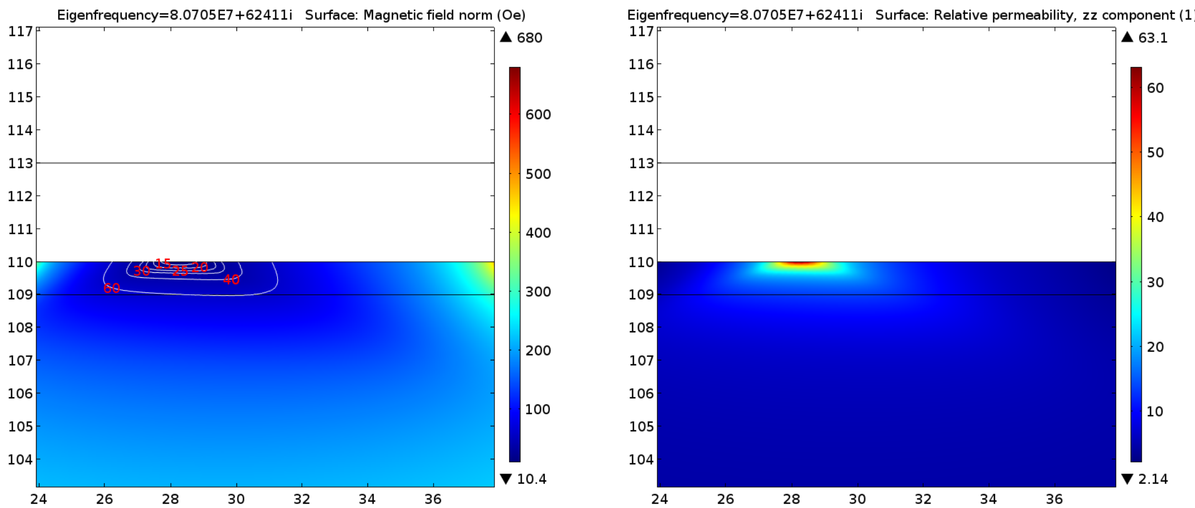

Fig. 7. Maps of magnetic field and permeability near the edge of the garnet block; Iw = 50 kA.

Gyromagnetic resonance frequency can be calculated using the next expression:

$$H_{gm}\ (\mathrm{Oe}) = f\ (\mathrm{MHz})/2.8$$

For the 81 MHz frequency, $H_{gm} \approx 30$ Oe; magnetic field at the top portion of the ferrite material in Fig. 6 is lower than the resonance level. This explains high RF loss in the cavity at low bias.

An additional remark must be made about intrinsic accuracy of the modeling: the model of the RF loss in gyrotropic media employed during modeling uses linear approximation of the expressions derived in [6], so satisfactory precision of the modeling can only be expected when the frequency is sufficiently far from the resonance.

To find a reason of significant deviation of the calculated and measured values of the quality factor, let's first compare vendor's data for the material used in the test cavity and in the cavity studied in [3].

Table 3. Garnet material data

	Material in [3]	Material in the Test cavity
Dielectric permittivity ε	13.86	13.80
tg (δ_ε)	0.0001	0.0001
4π·Ms (Oe)	764	795
-3 dB L.W. (Oe)	24	37.6

We see that the 9.4 GHz resonance line of the material used for the test cavity is significantly wider than what we used so far for the modeling. This line width corresponds to the value of the loss factor **α = 0.00564.** Results obtained by modeling that used the new value of the loss factor are shown in Fig. 8 and compared with what was shown in Fig. 6.

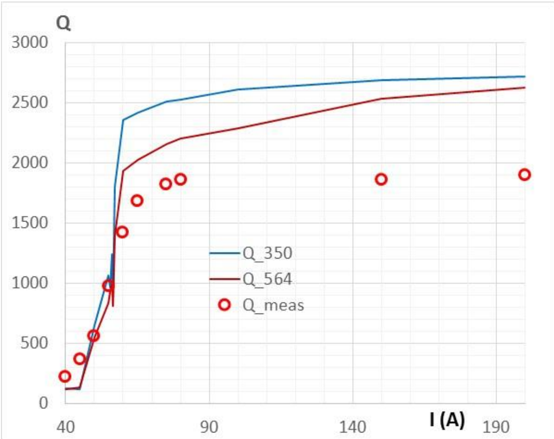

Fig. 8: Quality factor of the test cavity: measured and calculated using different values of the loss factor.

Calculated high bias quality factor is still much higher than what was measured. Explanation of this inconsistency using the argument of possible higher resistivity of the cavity material (copper) seems **unrealistic** as it requires having ρ = $4.3 \cdot 10^{-8}$ Ohm-m (see Fig. 9) with normally accepted $2 \cdot 10^{-8}$ Ohm-m level.

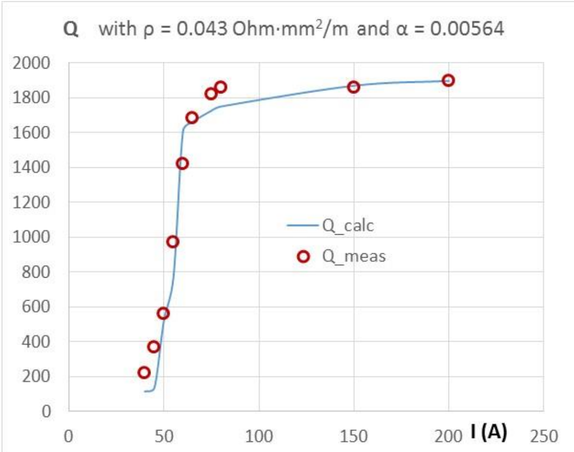

Fig. 9. Measured and calculated quality factor of the test cavity with α = 0.00564 and ρ = $4.3 \cdot 10^{-8}$ Ohm-m.

To get an alternative explanation of the lower measured quality factor of the test cavity, the cavity without garnet material was modeled and measured. Frequency of the “bare” cavity is ~132 MHz; expected quality factor with the $4.3 \cdot 10^{-8}$ Ohm-m wall material resistivity is 2675. Quality factor Q = 1900 was measured in the bare cavity (Fig. 10) - much lower than expected.

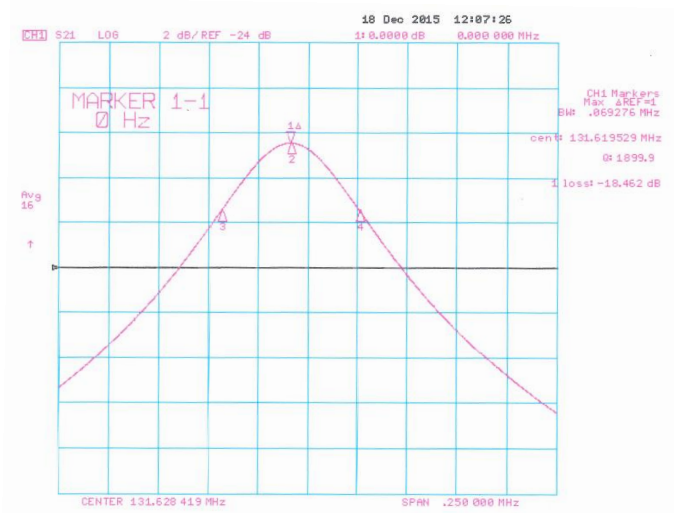

Fig. 10. Results of the RF measurements made on the “bare” test cavity.

Further investigation provided the explanation of why the quality factor is so low: poor mechanical contact between different parts of the cavity led to RF leakage. Attempts to mitigate the leakage resulted in the maximum measured value of the quality factor of ~2500. Effective resistivity of the cavity wall material that explains the maximum measured quality factor of the bare cavity is $4.88 \cdot 10^{-8}$ Ohm-m; corresponding conductivity **σ = 2.05E7 Sim/m**.

The computational model of the cavity containing the garnet tuner was updated using this conductivity value; in Fig. 11 the modeling results are compared with the measurement data.

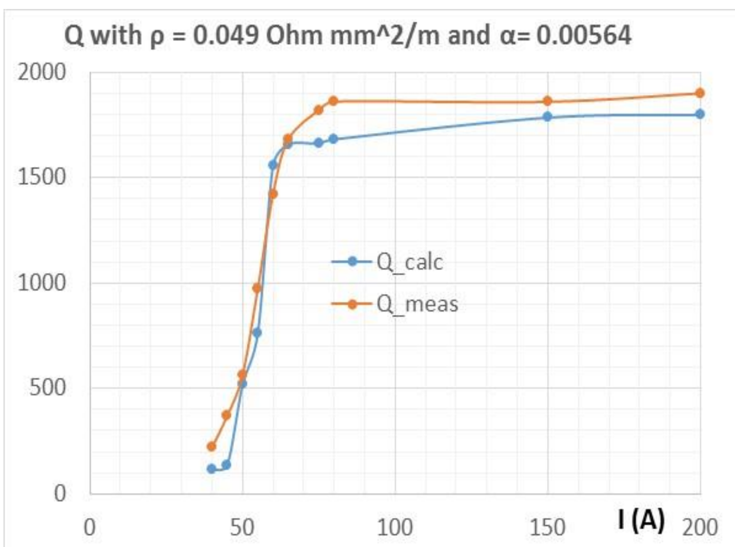

Fig. 11. Comparison of the measured quality factor with the calculated using the effective conductivity of walls that mocks the radiative power loss.

Summary

To understand how accurately a tunable transversely-biased ferrite-loaded RF cavity can be modeled by using the approach developed in [4], RF measurements were made using specially designed test RF cavity in the range of bias currents that resulted in the resonance frequency change between 75 MHz and 110 MHz. The measurement data were compared with predictions of the modeling. It was found that quality of the test cavity fabrication can distort the quality factor data obtained by the measurements because of significant radiation due to the poor mechanical contact between the current-carrying parts of the cavity. After this radiation is taken into account, the measurement data becomes consistent with the prediction of the modeling.

Set of data representing the static and RF properties of the garnet material must be well defined to avoid disagreement between the measured and calculated properties of the cavity. Comparison of samples of the material procured at different times show that one can expect significant difference in the Line Width parameter that directly affects quality factor behavior in the vicinity of the gyromagnetic resonance and local RF loss in the material. A way must be suggested on how the quality of the AL-800 garnet material could be guaranteed and/or checked before the assembly of the cavity is attempted.

It is also worth to mention that the static magnetic properties of the material used in the Test cavity were not measured; they were assumed identical to those found in [2]. Validity of this assumption must be verified; results of the modeling will inevitably change if it is not true.

References:

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